

FRACTURE BEHAVIOUR OF P/M Cr-V LEDEBURITIC STEEL WITH DIFFERENT SURFACE ROUGHNESS

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Resume

The samples made from the Vanadis 6 PM ledeburitic tool steel were surface machined to different quality and heat treated by standard regime of the processing. Three point bending tests were carried out on processed samples. It was found that the flexural strength decreased with decreasing surface quality. The lowering of flexural strength has been accompanied with the decrease of the plastic component of plastic straining preceding to fracture initiation (work of fracture) of the material. It indicates that the surface roughness leads to the crack initiation before a larger plastic deformation of the material can be developed. Based on the results it can be suggested that to prevent the cracking of tools in the practice it is essential to make a surface machining (grinding, lapping, polishing) to as high quality as possible.

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1. Introduction

Ledeburitic steels fabricated by powder metallurgy of rapidly solidified particles (PM ledeburitic steels) became a great importance in variety industrial applications like sheet metal working, tubes drawing and other cold work applications, mainly in the automotive industry.

The most important advantage of PM ledeburitic steels is their much finer and isotropic microstructure compared to the steel manufactured by conventional ingot metallurgy. This is reflected also by higher level of mechanical properties, mainly in resistance against initiation of brittle fracture.

For ledeburitic steels, the resistance against brittle fracture initiation is commonly evaluated by using static three point bend test. This method is very sensitive to any structural defects, typically pores, inclusions, carbide bands and clusters [1,2]. For newly developed ledeburitic steels, however, these types of structural defects are not typical since the

manufacturing route of the material preparation is conducted carefully and controlled accurately. Resulting of that, the content of impurities (sulphur, phosphorus) does normally not exceed 0.01% and the size (diameter) of fine and uniformly distributed carbides is usually well below 3 μm . Finally, residual porosity of PM ledeburitic steels is close to zero.

The tools from ledeburitic steels are made by various mechanical machining operations. These procedures, like turning, milling, grinding or drilling result in a different surface quality/roughness of manufactured tools. Various final mechanical operations follow also after heat treatment, including grinding, polishing and/or honing. Different grooves are covering the steel surface, these geometrical defects are usually quantified by parameters of surface roughness.

It is known that the resistance against the brittle crack initiation of the common ledeburitic steels differs substantially from that of PM

ledeburitic steels. On the other hand, there are much smaller differences in the fracture toughness between these two types of materials [3-5]. This is the reason why also the PM ledeburitic steels are sensitive to various mechanical micro-notches, being formed by surface roughness.

For the ledeburitic steels made by conventional ingot metallurgy, the effect of surface roughness on three point bending strength has been analysed several times recently. Firstly, Geller [6] has published experimental results concerning the R8 (0.9 %C, 4.1 %Cr, max. 1 %Mo, 2.3 %V, 9.25 %W) ledeburitic tool steel. He found out that the bending strength was lowered to 94% for the fine ground surface and to 75 % for milled surface, both compared to mirror polish. Spies, Riese and Hoffmann [7] have investigated the effect of surface quality on the three point bending strength of the M2 ledeburitic steel, austenitized at 1220 °C, quenched and triple tempered at 550 °C. The testing parameters

were: specimens dimensions 10 x 10 x 100 mm, loading rate of 1 mm/min. It was found that the three point bending strength decreased from 3780 MPa at $R_a = 0.1 \mu\text{m}$ to 3700 MPa at $R_a = 0.5 \mu\text{m}$ and to 3600 MPa at $R_a = 1 \mu\text{m}$.

For the ledeburitic steels made by powder metallurgy of rapidly solidified particles, there are not available data, concerning the effect of surface roughness on fracture behaviour, in technical literature. These materials, however, are widely used in various industrial applications, mainly in sheet metal working in an automotive industry. Therefore we considered as a very important task to investigate this problem.

2. Experimental

The Cr-V ledeburitic cold work tool steel Vanadis 6 was used for the experiments. The chemical composition of the material is given in Table 1.

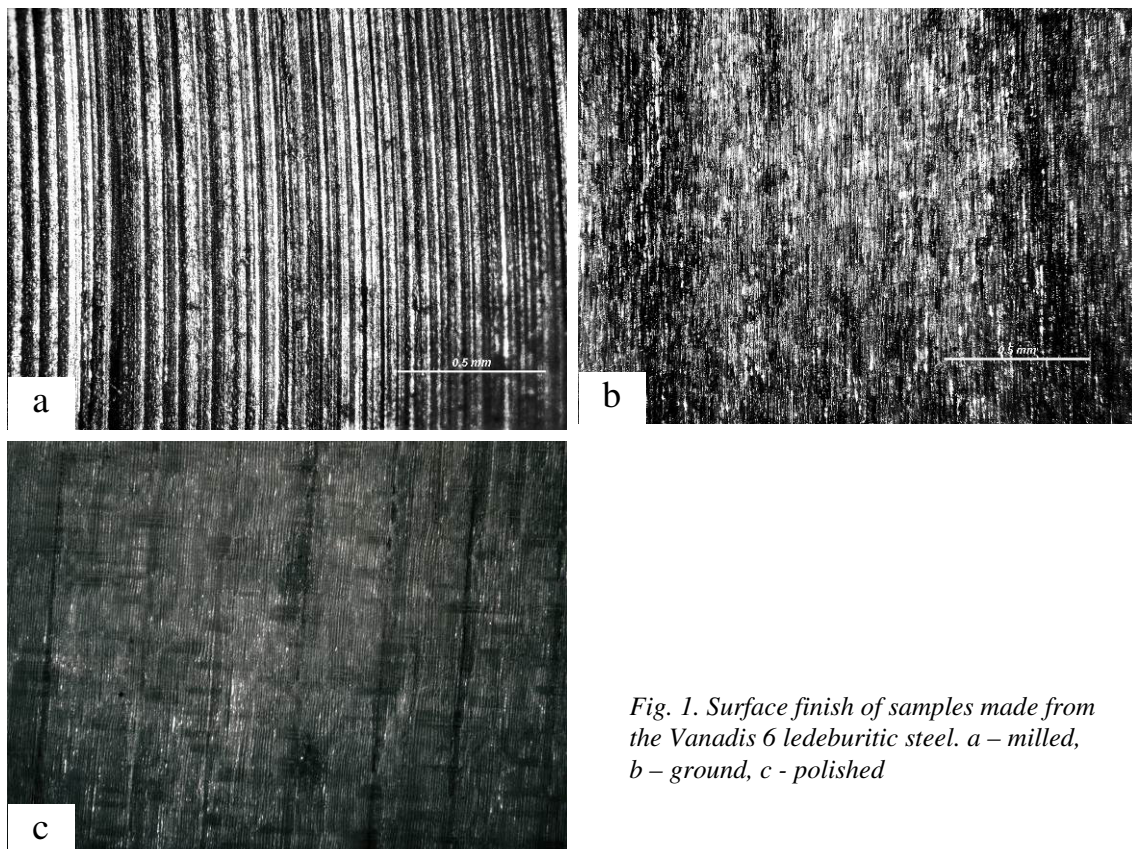


Fig. 1. Surface finish of samples made from the Vanadis 6 ledeburitic steel. a – milled, b – ground, c - polished

Table 1
Chemical composition of evaluated material.

Material	C	Si	Cr	V	Mo
Vanadis 6	2.1	0.8	7	5.8	1.5

For flexural strength determination flat specimens of the dimensions 10 x 1.5 x 55 mm were used. Samples for toughness determination have not been standardised yet so based on preliminary consideration it was suggested to test thing samples supposing the surface quality can affect the fracture behaviour and final values of flexural strength. The samples were machined (milled) to a surface roughness of 6 μm , Fig. 1a. Some of them were subsequently ground to a roughness of 0.2-0.3 μm , Fig. 1b. A set of samples was finally fine polished, Fig. 1c. All the specimens were heat processed according to regime recommended for cold work applications by steel producer, e.g. vacuum austenitizing at 1050 °C for 30 min., quenching with a 6 bar nitrogen gas and immediately twice tempering, each cycle at 550 °C for 1 h.

Microstructural analysis were carried out using the light microscope NEOPHOT 32 and scanning electron microscope JEOL 5410 M. Also for the fractographical analysis of fracture surfaces obtained by three point bend tests, the JEOL 5410 M microscope was employed. Hardness of the material in the as-received as well as heat processed conditions was measured by the Vickers hardness tester at a load of 98.1 N (HV 10) and loading for 10 s. Each specimen was measured 10 times and the average hardness value was then calculated.

Three point bend tests were performed on standard test machine Instron 8862 with 100 kN load frame capacity and 5 kN load cell capacity. Distance between supports was 40 mm. Tests have been done at an ambient temperature and a loading rate of 2 mm.min⁻¹. The load and deformation (flexure) was recorded during the testing.

The bending strength was calculated using the formula:

$$R_{mo} = \frac{3F_f L_o}{2BW^2}$$

where R_{mo} is the flexural strength, F_f is the load at the fracture point, L_o is the distance between supports, B and W are the thickness (dimension perpendicularly to loading direction, typically 10 mm) and width of the specimen (dimension in direction of load action, nominally 1.5 mm), respectively.

3. Results and discussion

The microstructure of the as-received material consists of spheroidized pearlite (carbides + ferritic matrix) and fine, uniformly distributed secondary and eutectic carbides, Fig. 2a.

Detail micrograph in Fig. 2b made by scanning electron microscope at higher magnification shows that eutectoid carbides are very fine – with a size well below 1 μm . Other carbide particles, e.g. secondary and eutectic phases, are of a size between 1 and 3 μm . Hardness of as-received steel was 284 HV 10.

From the load – deflection traces, the elastic and plastic energies before the fracture were determined, assuming that the instable fracture propagation fracture followed the initiation immediately. These energies, standardly called as work of fracture (total, elastic, plastic), were determined as corresponding area below the load – deflection traces up to fracture point. Fracture propagation is then controlled by accumulated elastic energy in the specimen. As a quantitative measure representing the effect of the surface roughness on the fracture behaviour was then considered the plastic part of the total deformation energy - plastic component work of fracture (WOF_{pl.}). The results of investigations are summarized in Table 2.

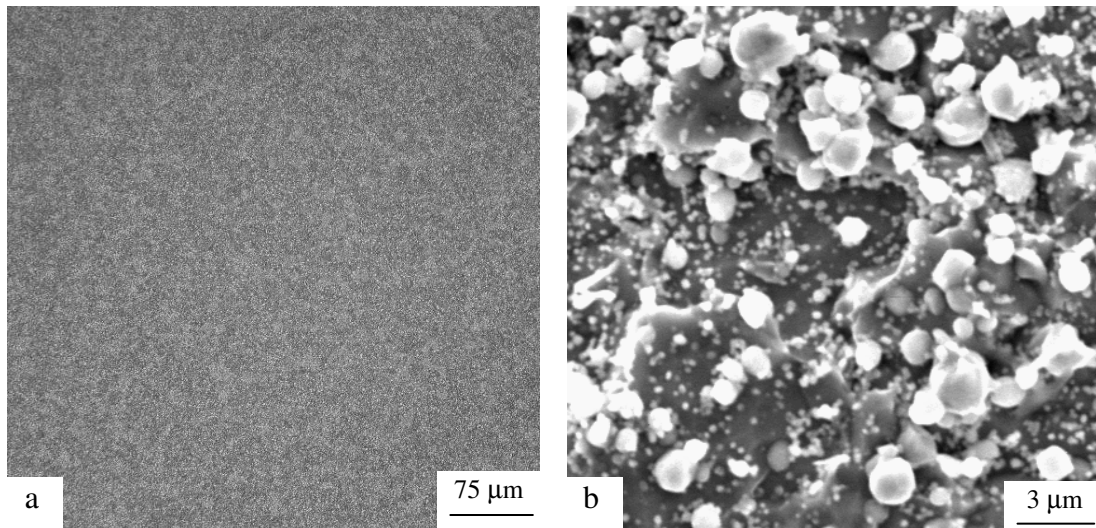


Fig. 2. Microstructure of PM ledeburitic steel Vanadis 6, as-received.
a – overview (light microscopy), b - detail (SEM)

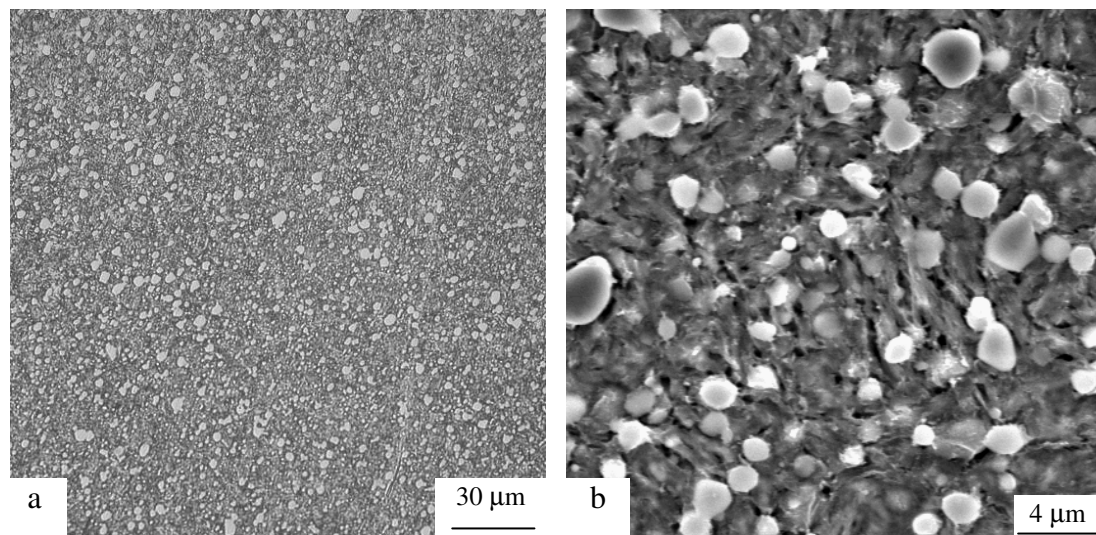


Fig. 3. Microstructure of PM ledeburitic steel Vanadis 6 after performed standard heat treatment.
a – overview (light microscopy), b - detail (SEM).

The microstructure after the heat treatment is in Fig. 3a (overview) and Fig. 3b (detail). The matrix consists of the tempered martensite. Eutectoid, as well as a part of secondary carbides were dissolved completely during the austenitizing of the material. Other part of secondary carbides, however, remained almost completely undissolved and they are visible as finer globular particles on the micrograph. After the heat treatment, the average hardness of the material was 724 HV 10.

Figure 4 shows the dependences load vs. bending for the samples of all three analysed

surface qualities. It can be seen that there are differences between the traces. These differences can be demonstrated as by the decreasing of the coordinate angle of the linear part of the curvatures with the increase of surface roughness, so by the decrease of the load at the fracture point.

Differences in the loading history until the fracture were reflected also by flexural strength in three point bending, Fig. 5. It is clear that especially the samples with milled surface possess significantly lower flexural strength.

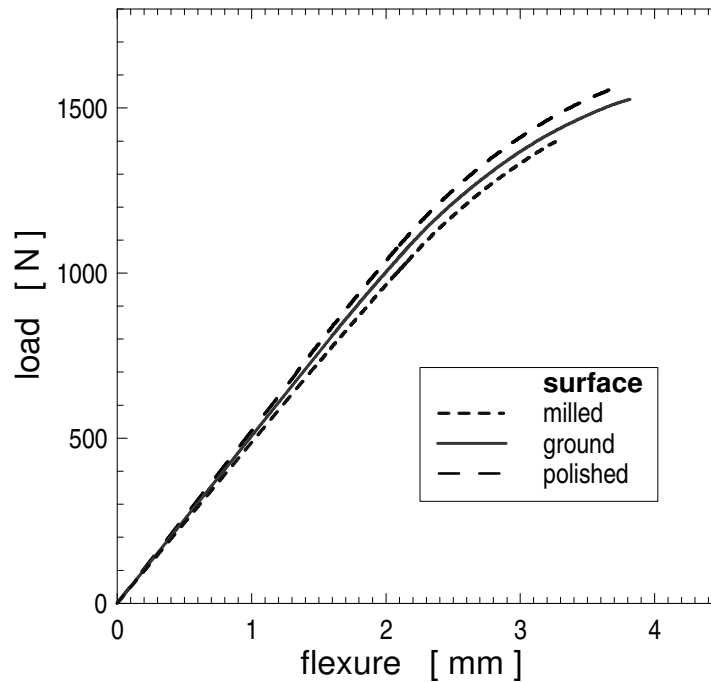


Fig. 4. The traces load – flexure deformation for various surface quality of heat processed Vanadis 6 ledeburitic steel

Measured and determined characteristics of the bending tests, including determined values of deformation energy, are summarized in Table 2.

As shown clearly, both the plastic energy as well as the three point bending strength decreases as the surface roughness increases. This behaviour is evident also from Fig.6.

Results of the determination of plastic deformation energy indicate that increased surface roughness acts in favour of initiation of

fracture. Together with a low fracture toughness of the material after a given heat treatment [5] it leads also to easy propagation of cracks and practically immediate fracture.

Difference of the elastic part of the deformation energy cannot be attributed to the toughness of testing machine. However, there is not other explanation of different values at present since the physical properties of the samples material can be considered to be stable due to the same heat treatment.

Table 2

Measured and determined parameters of bending tests of the Vanadis 6 ledeburitic steel

spec. nr.	surface	thickness B [mm]	width W [mm]	Fracture load F [N]	Flexural strength R_{mo} [MPa]	WOF _{el} [J]	WOF _{pl} [J]	WOF _{tot} [J]
1	polished	10.012	1.497	1466	3920	0.891	1.14	2.033
2	polished	10.010	1.515	1557	4066	2.321	0.969	3.291
3	polished	10.009	1.490	1566	4228	2.459	1.283	3.743
11	ground	10.005	1.576	1554	3752	1.355	0.632	1.987
12	ground	10.006	1.521	1582	4100	2.369	0.962	3.331
13	ground	10.023	1.497	1526	4076	2.301	1.104	3.405
50	milled	10.017	1.517	1416	3585	1.125	0.262	1.387
51	milled	10.025	1.499	1339	3566	1.912	0.337	2.249
52	milled	10.070	1.540	1399	3515	2.006	0.489	2.495

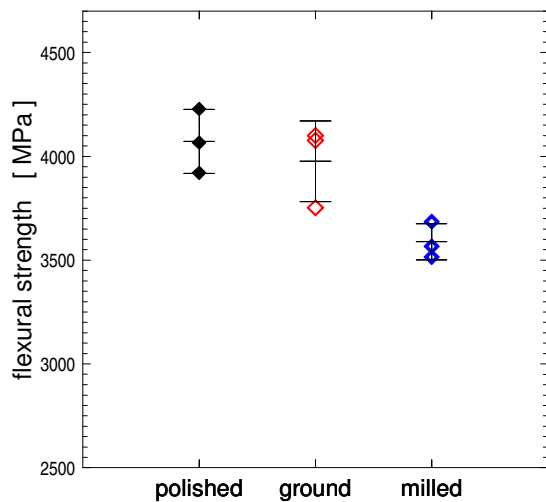


Fig. 5. Flexural strength for heat processed samples made from the Vanadis 6 ledeburitic steel with various surface quality

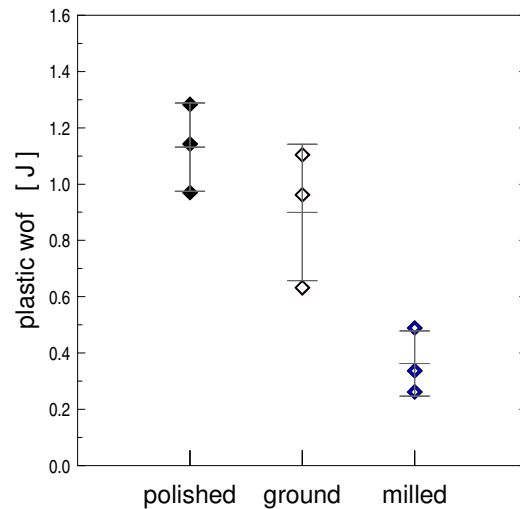


Fig. 6. Plastic work of fracture (component of deformation energy prior to fracture initiation) for the heat processed samples of Vanadis 6 ledeburitic steels with various surface quality

Also the microstructure of PM produced material Vanadis 6 can be considered to be homogeneous and no preferable orientation of carbides, for example, is expected.

Fractographical analysis has shown that the fracture surfaces, independently on the surface quality of the samples, exhibited also secondary cracks besides the main crack, Figs. 7a, d. Fracture surfaces have a typical morphology for a given type of materials, e.g. they display a dimple morphology with relatively low topography. More detailed analysis at higher magnification, however, indicates that for the samples with better surface quality (polished), the dimples are significantly deeper, compare Figs. 7b, c to Figs. 7e, f. This is due to higher level of plastic deformation before the fracture and it is in good agreement with the results of three point bending strength as well as with the determination of the plastic deformation energy, see Figs. 5, 6. These results show doubtless that also for relatively brittle materials like quenched and tempered PM ledeburitic steels, the surface quality plays

an important role in their fracture behaviour, especially in the initiation stage of the brittle fracture. This is also very important for final users of the materials, like tool manufacturers and users, and it gives a strong recommendation to make the surface as high quality as possible to prevent the initiation of cracks and to ensure the service reliability of tools.

4. Conclusions

- 1) The best values of flexural strength obtained in three point bending of the quenched and tempered Vanadis 6 ledeburitic steel were achieved when the samples were polished. The grinding of samples supplied a little worse results and the milling a surface finishing led to clearly lowest values of bending strength.
- 2) Plastic work of fracture initiation was also determined to be the highest for the polished samples. It means that the best surface finished material is less sensitive to the brittle fracture.

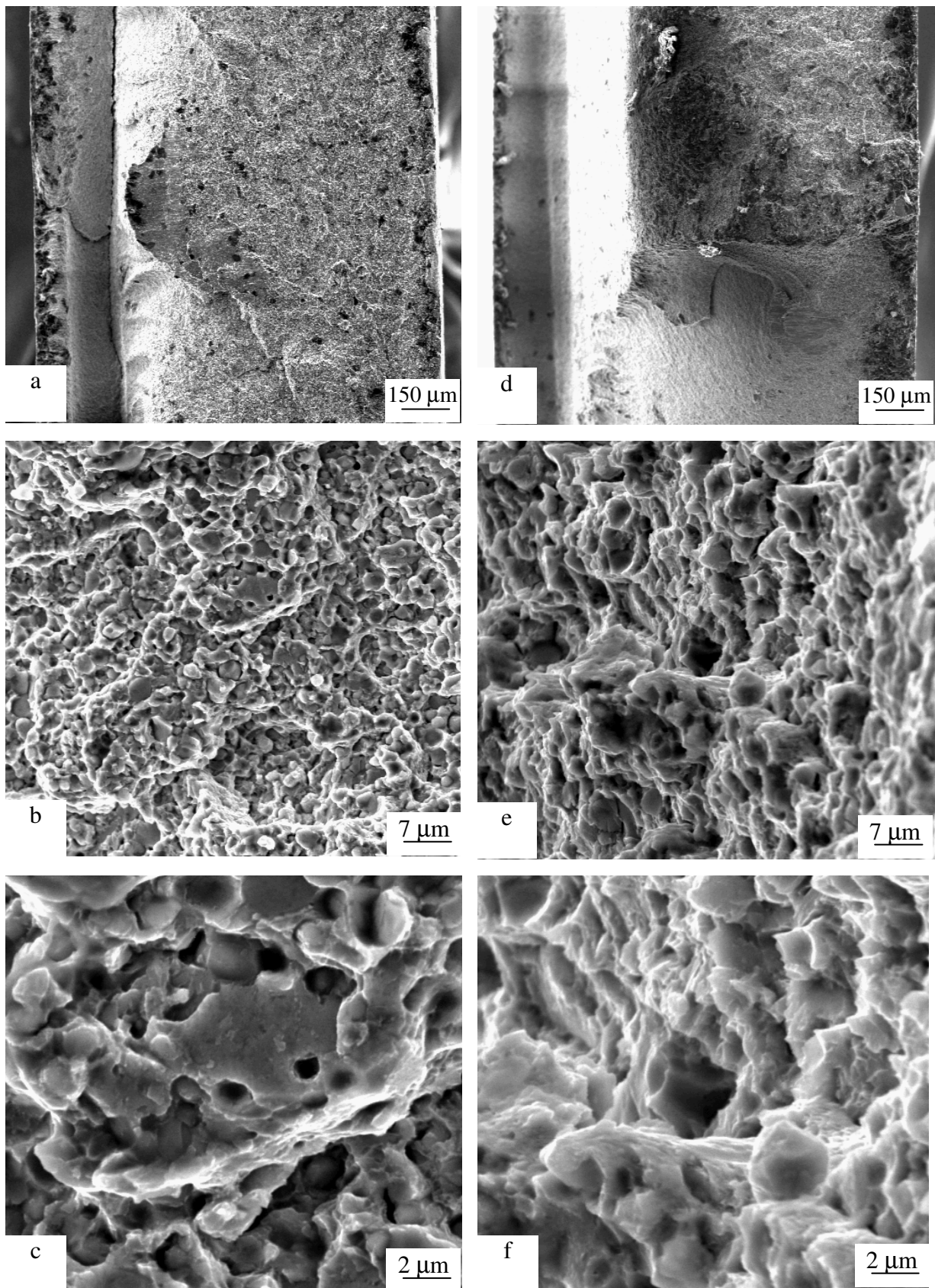


Fig. 7. Fracture surfaces of samples made from the Vanadis 6 ledeburitic steel after the three point bending tests. a, d, c – milled surface, d, e, f – polished surface.

- 3) Different values of plastic deformation energy are reflected also on fracture surfaces. The worse the surface quality the more flat is the fracture surface topography.
- 4) For the practical purposes, to minimize the probability of premature and sudden unstable damage of tools made from PM ledeburitic steels it is necessary to ensure the best quality of the surface after machining operations.

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